Resolution Limits of Pixellated Optical Components

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ABSTRACT

Pixellated optical components, for example generalised confocal lenslet arrays (GCLAs), enable the design of optical devices which cannot be realised without introducing pixellation or a similar compromise. A key concern is the degradation of imaging quality due to the combined effects of diffraction, worst for smaller pixels, and the visibility of the pixels. Here we examine the effects of these two factors on image quality through use of our custom raytracer, Dr TIM. We also outline future work in developing these ideas more rigorously and applying the conclusions to more complicated devices.

Keywords: Geometric Optics, Imaging Systems, Artificially Engineered Materials

1. INTRODUCTION

Most common optical systems, such as telescopes or common spectacles, consist of components which are always designed to preserve continuity of transmitted phase fronts. On the one hand this minimises diffractive effects, but on the other it limits the possibilities of these systems as the ray fields that correspond to continuous phase fronts are curl-free.

Here we consider optical devices which preserve phase continuity over small subareas, the *pixels*, but introduce discontinuities between these areas of local continuity. These devices can perform in ways not possible for devices which do not introduce these discontinuities, for example performing generalised refraction in air.[1] They can form imaging devices, such as those found in compound insect eyes;[2] they allow integral imaging or light field imaging[3] which can, in principle, be used to create novel pixellated transformation-optics devices.[4,5] Any device consisting of such pixels we describe as *pixellated* and the study of these devices we call *pixellated optics*.

Crucial to determining the efficacy of these devices is tuning the pixel size to minimise diffraction whilst remaining as small as possible such that the pixels themselves remain invisible. Here we consider a planar surface capable of generalised refraction, exemplified by generalised confocal lenslet arrays (GCLAs), and identify the parameters which determine the resolution of such a system. Will we show how an understanding of these parameters can lead to an quantitative understanding of the limitations incumbent on such devices.

2. GENERALISED CONFOCAL LENSLET ARRAYS (GCLAS)

Our exemplar for pixellated optical components we use generalised confocal lenslet arrays (GCLAs),[6] which consist of arrays of pixels comprising miniature telescopes formed by a pair of confocal lenslets. These miniature telescopes, or telescopelets, may be Galilean of Keplerian in design. We consider only light that passes through the *corresponding* pair of lenslets which form a telescopelet. Any light which does not exit through the corresponding lenslet will undergo non-standard refraction,[7,8] leading to secondary images. Here we assume that such stray light is eliminated, for example by baffles separating neighbouring telescopelets.

We abstract here simple GCLAs to more general pixellated components, as follows. Firstly, as shown in Fig. 1(a), GCLAs aperture the part of the beam that passes through an individual pixel to a width w that is smaller

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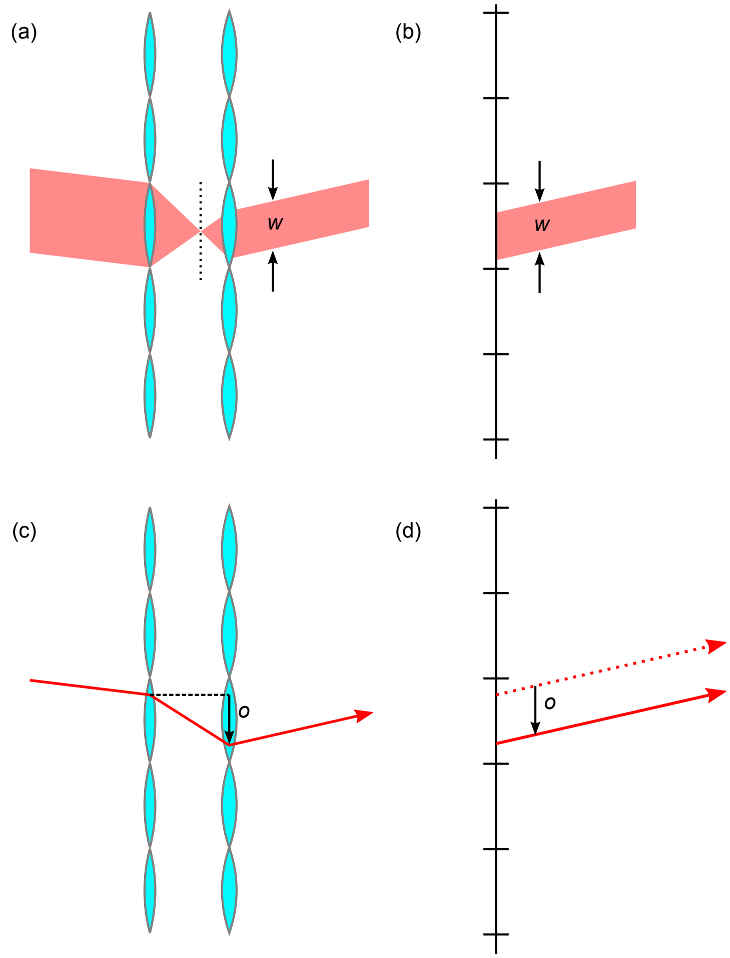

Figure 1. Effects of pixellation, in the examplar case of simple GCLAs and abstracted. (a) The part of the beam that passes through an individual telescopelet is apertured to a width w equal to, or smaller than, the pixel width, W. This leads to diffraction. (b) The aperturing also happens in the abstracted component. Ray-optically, we model it as a blur of the light-ray direction over the angular width of the central diffraction maximum. (Bottom) . (c) In GCLAs, individual light rays experience a transverse ray-position offset, o. Depending on a light ray's direction and the precise position where it hits the first lens, o takes values in the range $-W \leq o \leq +W$. (d) In the abstracted component, o takes random values in the same range.

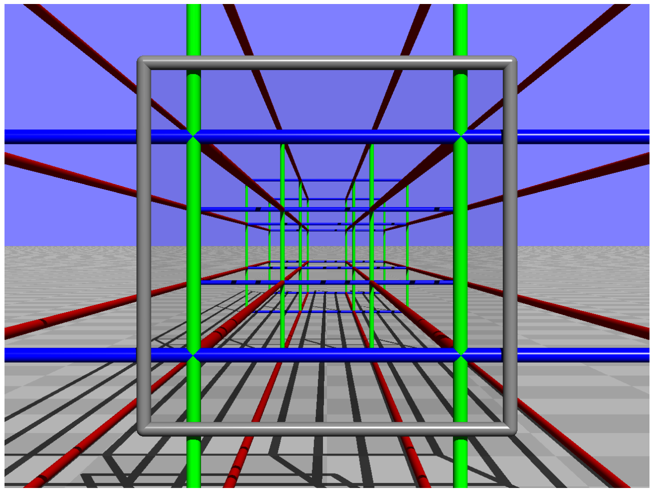

Figure 2. Scene comprising a checkerboard floor and a cylinder lattice seen through a transparent window that has no effect on transmitted light rays other than slight reduction in brightness. The window is framed by grey cylinders and positioned immediately in front of the closest cylinders in the array. The image is a raytracing simulation was performed using our custom raytracer Dr TIM.[9, 10]

than the pixel width, W. Such aperturing also occurs in the abstracted pixellated component (Fig. 1(b)). We model it as a random change of the light-ray direction, such that the new light-ray direction lies within the angular range of the central diffraction maximum that corresponds to an aperture of width w. Secondly, light rays experience a transverse position offset o on transmission through GCLAs (Fig. 1(c)). In the GCLAs shown, the value of o can range from $-W$ to $+W$. In the abstracted pixellated component (Fig. 1(d)), a transverse position offset in the same value range occurs.

3. BLURRING DUE TO PIXELLATION

The effects of pixellation described above lead to blurring of the view created by pixellated components.

As a baseline we consider a planar interface that has no effect on transmitted light rays other than a slight brightness reduction. The simulated view of a scene comprising a checkerboard floor and a cylinder lattice through this interface is shown in Fig. 2.

The view is, of course, unchanged by the interface (apart from slight brightness reduction) — the interface has trivially imaged every point in the scene to its original position. But for our purposes it does not matter whether the way by which the interface creates an image is trivial or fascinating; all that matters is that the interface creates an image. We use this to simulate the effect of pixellation. Fig. 3 shows the simulated views through the same interface with different combinations of the imperfections present.

In Fig. 3(a), the interface exhibits only diffractive blur. As already mentioned earlier, we simulate this effect as a light-ray-direction blur across the entire solid angle of the central diffraction maximum that corresponds to square pixels. As a simple approximation to the real situation, the outgoing ray directions are uniformly distributed across this solid angle. It can be seen that the blurring of images produced by the interface depends on the distance of the image from the interface: if the image is close to the plane of the interface, there is little blurring (in the same way in which an object immediately behind a toilet window, which also blurs light-ray direction, is still recognisable); the further away the image is from the interface, the more blurred it is.

In Fig. 3(b), the interface only offsets the position from which light rays leave the interface in the transverse direction. In each direction that corresponds to the side of the square pixels, the offset is uniformly distributed over the range $-W$ to $+W$ (where W is the side length of the pixels). It can be seen that images close to the interface now appear most blurred. The blurring decreases with distance from the interface; infinitely distant objects, such as the horizon, appear sharp.

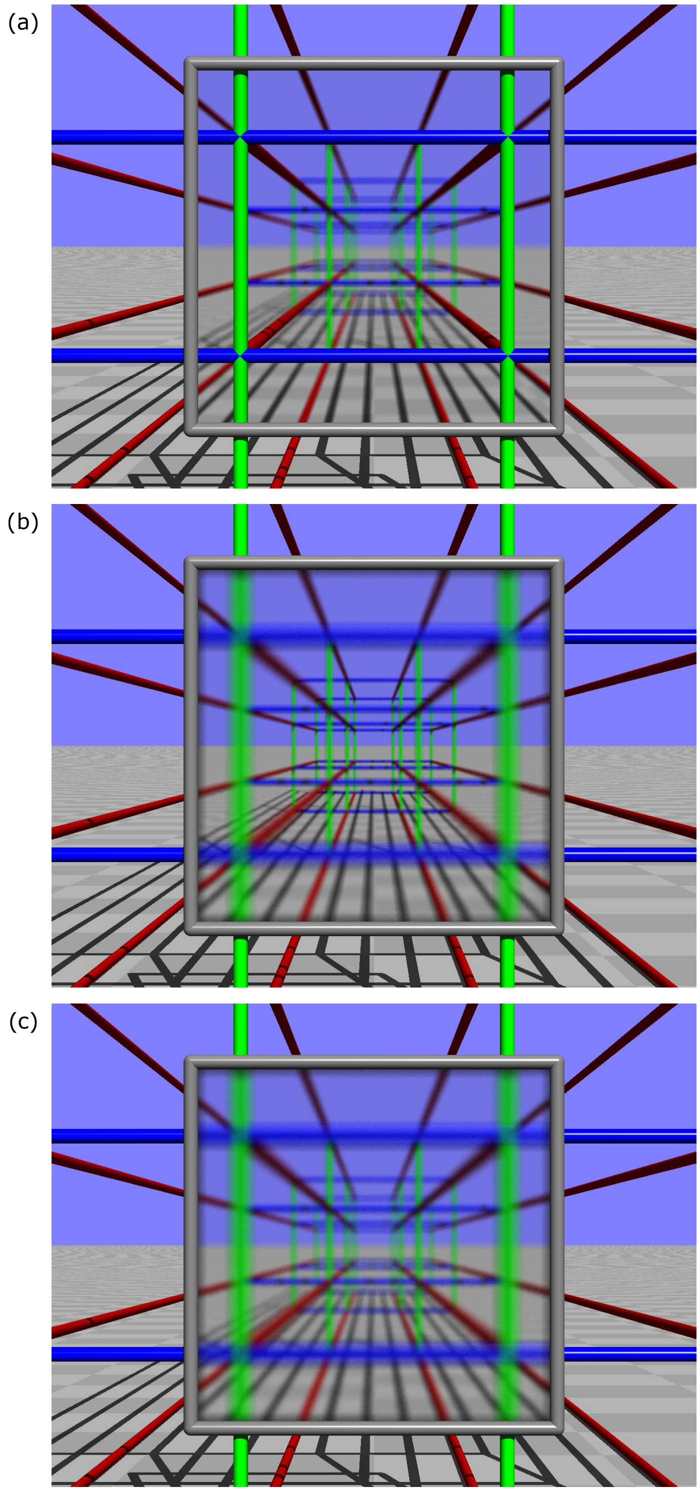

Figure 3. Visual effect of different kinds of blur due to pixellation. The images show a cylinder lattice seen through a pixellated window, which is contained within the grey frame. (a) Diffractive ray-direction blur increases with distance of the object from the window. (b) Ray-offset blur decreases with object-window distance. (c) Combined effect.

Finally, Fig. 3(c) shows the view through an interface in which both diffractive blur and ray-position offset are present. In the case shown, images produced by the interface appear more or less uniformly blurred independent of distance from the interface.

Fig. 4 shows the effect on diffractive blurring of varying the distance between the interface and the observer. When the interface is placed immediately in front of the closest cylinders (a), these are seen essentially sharp. Images seen further from the interface are blurred. As the interface is moved closer to the observer (b), the closest cylinders become noticeably more blurred. More distant images also become more blurred, but this is harder to see here. When the interface is positioned immediately in front of the observer (c), all images appear uniformly blurred.

Similarly, Fig. 5 shows the effect of varying the interface-observer distance on apparent blurring due to a random ray-position offset. In contrast to the case of diffractive blurring, blurring due to a random ray-position offset does not depend on the interface-observer distance.

4. DISCUSSION AND FUTURE WORK

Pixellated devices offer opportunities for geometric optics to do a wide range of novel things, including transformation optics applications usually reserved for metamaterials. They can achieve this by allowing for very generalised laws of refraction and imaging.

However these devices have an unavoidable tension in their design; larger pixels will minimise or effectively eliminate visible diffraction but will in turn result in noticeable pixel visibility whilst smaller pixels will have large diffraction issues. Here we have identified the key components which impact on the resolution of these pixellated optical components.

There are two clear forward directions in which to take this work. The first is to use these outlines to develop mathematical tools and, in combination with the previously outlined parameters for GCLA construction, to find out under what circumstances these devices will work optimally. Elements such as the desired distance of the object form the device and viewer, the level of magnification the device is to achieve, and the wavelength around which it is to be designed will all play a role in this optimisation calculation.

The second direction is to develop a practical prototype device which allows for these principles to be empirically tested. Such a device would enable the impact of these blurring factors on the scene as seen by the viewer. It will also enable a rigorous study of how the device performs in terms both of resolution and of chromatic aberration.

With both of these we then hope to be able to construct devices with novel optical properties using pixellated optical components.

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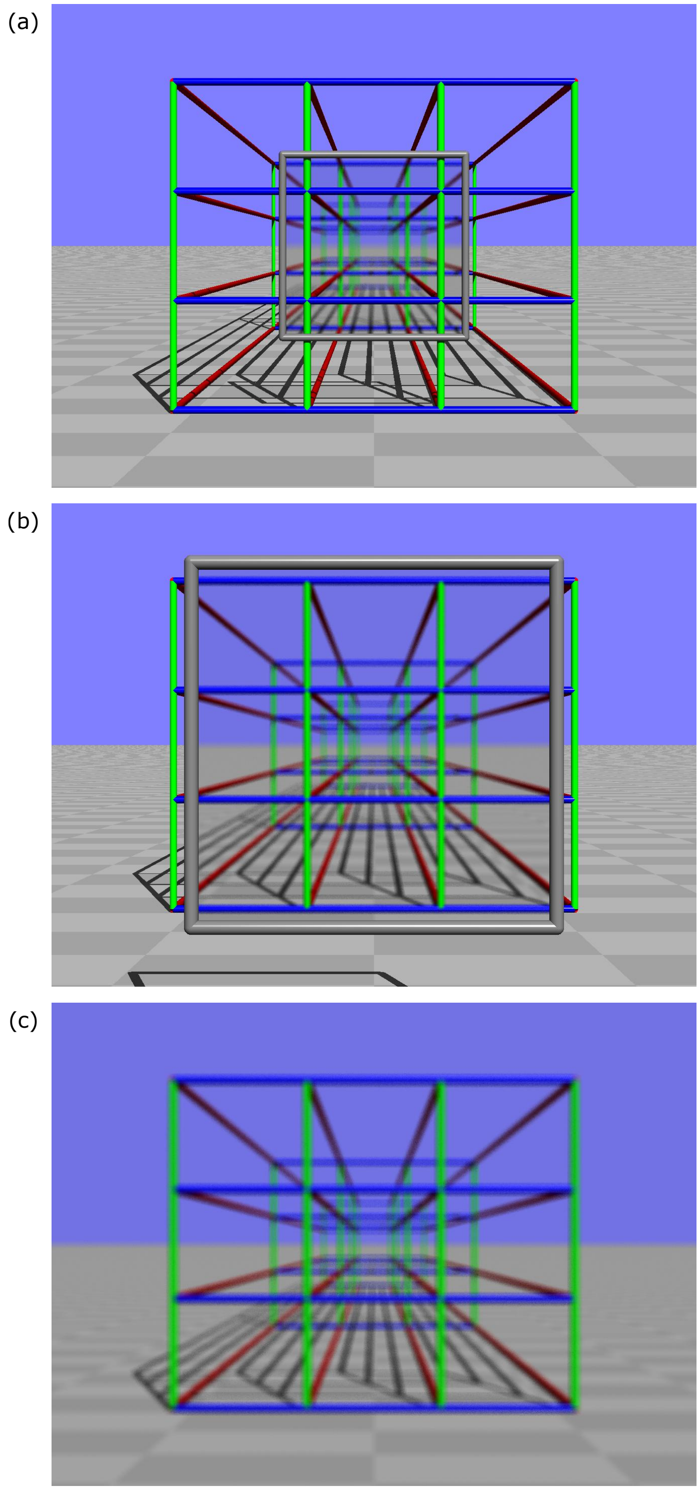

Figure 4. Dependence of diffractive blur on distance between the observer and the interface. (a) Interface placed immediately in front of the closest cylinders in the lattice; (b) interface half-way between observer and closest cylinders; (c) interface immediately in front of observer.

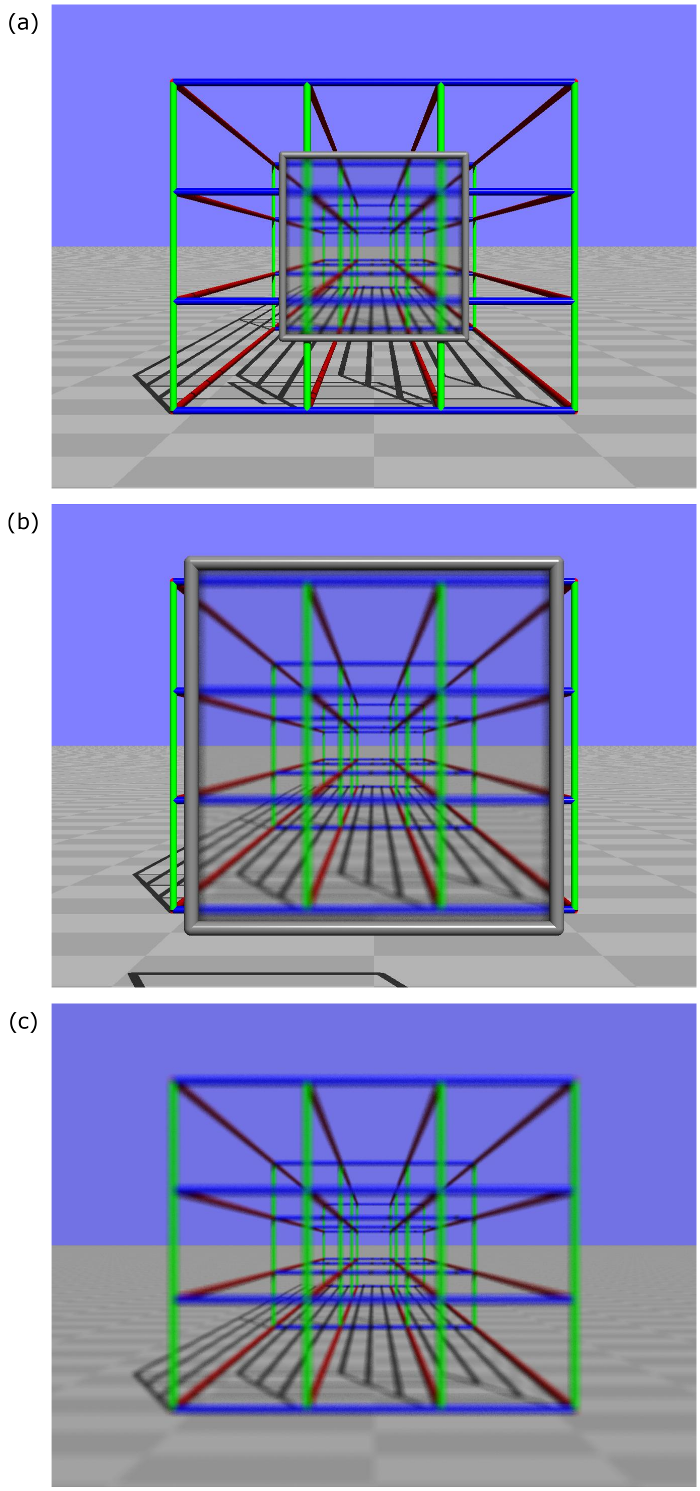

Figure 5. Dependence of apparent blurring due to ray-position offset on the observer-interface distance. (a) Interface placed immediately in front of the closest cylinders in the lattice; (b) interface half-way between observer and closest cylinders; (c) interface immediately in front of observer.

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